

Climate of Hawaii

Introduction

This publication consists of a narrative that describes some of the principal climatic features and a number of climatological summaries for stations in various geographic regions of the State. The detailed information presented should be sufficient for general use; however, some users may require additional information.

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The Means and Extremes of meteorological variables in the Climatography of the U.S. No.20 series are recorded by observers in the cooperative network. The Normals, Means and Extremes in the Local Climatological Data, annuals are computed from observations taken primarily at airports.

The editor of this publication expresses his thanks to those State Climatologists, who, over the years, have made significant and lasting contributions toward the development of this very useful series.

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Topographic Features- West and south of California, 2,100 miles away, lies Hawaii. Among the 50 states it is the only one surrounded by the ocean. It is the only state within the tropics. These features significantly affect its climate, as do its division into separate, widely spaced islands and its topographic diversity.

The islands of the State are the easternmost members of the Hawaiian Island Chain. This Chain extends for a distance of 2,000 miles from Kure and Midway Islands at the northwest to the Island of Hawaii at the extreme southeast end. There are six major islands in the State which occupy a narrow zone 430 miles long. From west to east these are: Kauai, Oahu, Molokai, Lanai, Maui and Hawaii. Taken together with the much smaller islands of Niihau and Kahoolawe, their total area is 6,424 square miles, about 30 percent greater than that of Connecticut. The approximate linear dimensions of the major islands and their areas are estimated as follows:

Island	Length (miles)	Width (miles)	Area (Square Miles)
Hawaii	93	76	4,021
Maui	48	26	728
Oahu	44	30	602
Kauai	33	25	553
Molokai	38	10	259
Lanai	18	13	141

The islands are summit portions of the long range of volcanic mountains that comprise the Hawaiian Chain. Kauai is geologically the oldest of the six major islands and is therefore most strongly eroded, as is evidenced by the deeply cut Waimea Canyon in the western half of the island and by the broadly eroded valley lands in the eastern half. Hawaii is geologically the youngest. Its dominant physiographic features are the large mountain masses of Mauna Loa and Mauna Kea, both of which rise to over 13,000 feet above mean sea level and both of which have suffered only slight erosion. The four major islands lying between Kauai and Hawaii are intermediate in age and in the amount of erosion to which they have been subjected. All the islands are bordered by coral reefs and have coastal cliffs, some of which are 300 to 3,000 feet in height.

The mountainous nature of Hawaii is indicated by the fact that 50 percent of the State lies above an elevation of 2,000 feet and 10 percent lies above 7,000 feet. However, the heights of the mountains vary greatly from island to island, shown in the following table:

Island	Maximum Elevation (feet) and Peak Name
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Hawaii	13,796	Mauna Kea
Maui	10,023	Haleakala
Kauai	5,243	Mt. Kawaiki
Molokai	4,970	Kamakou
Oahu	4,040	Mount Kaala
Lanai	3,370	Lanaihale

Almost half of the area of the State lies within five miles of the coast. Because of this extreme insularity the marine influence upon the climate is very great, yet the mountains, especially the massive ones on Hawaii and Maui, strongly modify the marine effect and result in conditions that are semi-continental in some localities. This results in climatic conditions of great diversity.

It is convenient to recognize seven climatic sub-regions in Hawaii. These are defined chiefly by the major physiographic features of the State and by location with reference to windward or leeward exposure. Since one region grades into another, it is not possible to draw sharp boundaries between adjacent regions. In general, however, the regions and their characteristics are as follows:

Windward Lowlands, generally below 2,000 feet on the north to northeast sides of the islands. This region lies perpendicular to the prevailing flow of the trade winds, and is moderately rainy, with frequent trade wind showers. Partly cloudy to cloudy days are common. Temperatures are more uniform and mild than in other regions.

Leeward Lowlands, except for the Kona coast of Hawaii which has a distinctive climate. In these areas, daytime temperatures are slightly higher and nighttime temperatures are slightly lower than in windward locations. Dry weather prevails except for an occasional light trade wind shower which drifts from the mountains and for periods of major storms. In some leeward areas, an afternoon sea breeze is common, especially in summer.

Interior Lowlands on Oahu and Maui, in the northeast these lowlands have the character of the windward lowlands; in the southwest, of leeward lowlands. The central areas are intermediate in character, and – especially on Oahu – are sometimes the scenes of intense local afternoon showers which form as a result of local heating of the land during the day.

Kona Coast of Hawaii, summer rainfall exceeds winter rainfall. There is a marked diurnal wind regime, with well-developed and reliable land and sea breezes, especially in the summer. Summer is also the season with a high frequency of late afternoon or early evening showers. Conditions are somewhat warmer and decidedly drier than in windward locations.

Rainy Mountain Slopes on Leeward Side, rainfall and cloudiness are very high, with considerable rain both winter and summer. Temperatures are equable. Humidities are higher than in any other region.

Lower Mountain Slopes on Leeward Side, rainfall is greater than on the adjacent leeward lowlands, but distinctly less than at the same level on the windward side except that the zone of maximum rainfall usually occurs just to leeward of the crests of the lower mountains.

Temperature extremes are greater than on the rainy slopes of the windward sides of the mountains, and cloudiness is almost as great.

High Mountains, above 2,000 or 3,000 feet on the high mountains of Mauna Kea, Mauna Loa and Haleakala rainfall decreases rapidly with elevation. Near the summits of Mauna Loa and Mauna Kea, rainfall is scant and skies are clear a high percentage of the time. Relative humidities may reach values of 10 percent or less. The lowest temperatures in the State are experienced in this region, with values below freezing being common.

The most prominent feature of the circulation of air across the tropical Pacific is the persistent trade-wind flow in a general east-to-west direction. In the central North Pacific, the trade winds blow from the northeast quadrant, and represent the outflow of air from the great region of high pressure, the Pacific Anticyclone, whose typical location is well north and east of the Hawaiian Island Chain. The Pacific High, and with it the trade-wind zone, moves north and south with the sun, so that it reaches its northernmost position in the summer. This brings the heart of the trade winds across Hawaii during the period May through September when the trades are prevalent 80 to 95 percent of the time. From October through April, Hawaii is located to the north of the heart of the trade winds. Nevertheless, the trades still blow across the islands much of the time, though with a frequency decreased to 50 to 80 percent in terms of average monthly values.

The dominance of the trades and the influence of terrain give special character to the climate of the islands. Completely cloudless skies are extremely rare, even though much of the time the dense cloud cover is confined to the mountain areas and windward slopes, while the leeward lowlands have only a few scattered clouds. Showers are very common; yet while some of these are very heavy, the vast majority are light and brief. Even the heavy showers are of a special character, in that they are seldom accompanied by lightning and thunder. Finally, the trade winds provide a system of natural ventilation much of time throughout most of the State and bring to the land, at least in the lower lying regions, the mildly warm temperatures that are characteristic of air that has moved great distances across the tropical ocean.

But the trades, though dominant, are not the only major dynamic element in the climatic setting of Hawaii. Major storm systems may influence all parts of the islands, and in some areas there is a local exchange of air between land and sea on a rhythmic, diurnal basis. There is also the fundamental diurnal cycle of night and day, and because Hawaii is in such a low latitude this cycle shows less variation in length than is found in any other state.

Major storms occur most frequently between October and March, inclusive. During this period there may be two to as many as seven major storm events. Such storms typically bring heavy rains; and are sometimes accompanied by strong winds, at least on a local scale. The storms may be associated with the passage of a cold front or low pressure.

The land-and-sea circulations are on a far smaller scale than the circulations of the major storm systems. The exchange of air often is confined to areas of tens of square miles or less. Circulations of this kind are most common on south and west coasts, in locations that are to the leeward of the trade winds and topographically sheltered from them. The Kona Coast of Hawaii, the Lahaina District of Maui, the Ewa-Waianae Coast of Oahu and the Barking Sands area of

Kauai are among the localities in which these circulations are common. These circulations have a well-marked diurnal rhythm. Between forenoon and early evening, air moves inland on a sea breeze. Sometimes these sea breezes are fairly brisk. During the night and until shortly after sunrise the air drifts back from land to sea. The return drift is usually very gentle, so much that it can barely be felt.

The land and sea breezes are controlled in part by the march between day and night. There is only a slight variation in length of night and day from one part of Hawaii to another, since the major islands of the State all lie within a narrow latitude band.

The relatively slight variations in the length of the daylight period in Hawaii as contrasted with other states, together with the smaller annual variations in the altitude of the sun above the horizon, result in relatively small variations in the amount of incoming solar energy from one time of the year to another. The solar energy that pours into the upper atmosphere above Hawaii each day varies by a factor of 50 percent from maximum to minimum. But at Washington, D.C., the daily receipt of energy is three times as great at time of maximum as it is at time of minimum; while at Anchorage it is 20 times as great.

This small variation in solar energy partly explains why seasonal changes in temperature are so slight throughout much of Hawaii. The other principal reason for the slowness of the variation is the virtually constant flow of ocean air across the islands. The air brings with it to the land the mild temperature regime characteristic of the surrounding ocean.

The rugged configuration of the islands produces marked variations in conditions from one locality to another. Air swept inland on the trade winds or storm circulation is shunted one way and another by the mountains and valleys and great open slopes. This complex three-dimensional flow of air results in striking differences from place to place in wind speed, cloudiness and rainfall. Together with variations in the elevation of the land, it results in differences in air temperature. Thus the climatic pattern reflects not only such dynamic elements as the trade-wind flow, the passage of storms, the seasonal rhythms of daylight and of solar heating, but also the static element of topography.

Native Hawaiians recognized only two seasons. *Kau* was the fruitful season, May through October, the season when the sun was directly or almost directly overhead, when the weather was warmer, and when the trade winds were more reliable. *Hoo-ilo*, November through April, was the season when the sun was in the south, when the weather was cooler, and when the trade winds were sometimes interrupted by other winds. If one uses a slightly different "calendar" with a winter season of seven months (October through April) and a summer season of five months (May through September), summer is very definitely the warmer season, the season with an overwhelming dominance of trade winds, and the season when widespread rainstorms are rare. Also throughout the lowlands, summer is the drier season in terms of average monthly rainfall, except on the Kona Coast (leeward coast) of the Island of Hawaii.

In terms of variations in climatic conditions from one part of the State to another, the most striking contrasts are those in rainfall. At one extreme, the annual rainfall averages 20 inches and less in leeward coastal areas and near the summits of the very high mountains, Mauna Loa

and Mauna Kea. Meanwhile, the annual average exceeds 300 inches along the lower windward slopes of these high mountains and of Haleakala and at or near the summit of the lower mountains of Kauai, Oahu and western Maui.

The temperature regime is not as variable from place to place as is rainfall; but there are major geographic differences, chiefly as the result of variations in elevations. The upper slopes of the high mountains lie well above the usual cloud zone and there are moderately wide swings in temperature from day to night. Thus in summer at an elevation of 8,000 feet it is not unusual to have daytime temperatures in the mid 60s and nighttime temperatures in the 40s; while in winter the range is typically from the 50s to near freezing or below. Diurnal temperature ranges are far less in the lowlands, with daytime temperatures commonly in the 70s to 80s and nighttime temperatures in the 60s to 70s. Both in the lowlands and at elevations up to about 4,000 feet the temperature differences from winter to summer are only four to eight degrees Fahrenheit (° F) in terms of differences in the mean daily maximum and mean daily minimum.

In general, the Hawaiian climate is characterized by a two-season year, by mild and fairly uniform temperature conditions everywhere except at high elevations, by striking marked geographic differences in rainfall by generally humid conditions and high amounts cloudiness except on the driest coasts and high elevations, and by a general dominance of trade-wind flow especially at elevations below a few thousand feet. How conditions differ in more detail from season to season and place to place is evident from the following summary, which treats specific aspects of the climate, discusses storms and other weather phenomena, and distinguishes among the principal kinds of climatic regions of the State.

Temperature- An outstanding feature of the climatic regime of Hawaii is the small annual temperature range. In downtown Honolulu the warmest month is August, with an average temperature of about 82° F the coldest, February, around 73° F – the range between the coldest and warmest months averages only nine degrees. At Hilo and Lihue, the range is five and eight degrees, respectively. While annual temperature ranges are almost as small as this in a narrow zone bordering the coast of California, throughout virtually all the remainder of the United States they are very much larger.

The extremely equable temperature conditions are associated with the relatively small seasonal variation in the energy received from the sun and especially with the mid-ocean location of Hawaii. The waters around Hawaii have an average temperature that ranges from a minimum of about 74° F between late February and early April to a maximum of 80° F in late September or early October. With temperatures almost as mild for hundreds of miles around, the air that reaches Hawaii is neither very hot nor cold.

Outside the dry, leeward areas, temperatures of 90° F and above are uncommon. In the leeward areas, temperatures in the low 90s may be reached, but temperatures much higher than these are unusual. The State's record high of 100° F was set at Pahala, on the south side of the island of Hawaii, elevation 850 feet, on April 27, 1931.

At times the upper slopes of Mauna Kea and Mauna Loa are white with snow. Under favorable circumstances, cold air formed above this snow cover on clear nights produces very low

temperatures at the highest elevations. Hawaii's record minimum, 12° F, was set May 17, 1979 at Mauna Kea Observatory, elevation 13,770 feet.

In exposed locations on the mountains, however, the cold air formed locally is often swept away and replaced by the far warmer air that is carried across and around the mountains by the upper winds. The local winds tend to move down slope at night and upslope during the day also inhibit the formation of extremely cold air.

At elevations below 1,000 feet, the lowest nighttime temperatures on record have been in the 50s, except in relatively cloudless areas such as central Maui and the leeward coasts where temperatures in the upper 40s have occurred. Here again, these are extreme values, and it is possible for several years to pass before temperatures near 50° F are experienced in any locality near sea level.

In general, lowland temperature conditions in all but the driest areas are represented by the values for Honolulu, Hilo and Lihue. Conditions in the driest areas are represented by the values given later for Mana, Kauai, Waianae, Oahu and Lahaina, Maui – all of which lie on leeward coasts in areas that are very dry and relatively free of clouds.

In these dry areas as throughout Hawaii, August and September are the warmest months of the year. August tends to be the warmest on Kauai, the northernmost island of the State, and September the warmest on Hawaii, the southernmost island. This occurrence of highest temperatures in late summer and early autumn is typical of areas that receive fresh ocean air a high percentage of the time.

As in all mountainous areas, the wind patterns in Hawaii are exceedingly complex. Though the trade winds are fairly constant in speed and blow a high percentage of the time across the adjacent water and onto the islands, the relatively uniform trade-wind flow is distorted and disrupted by the geography. In addition, there are local wind regimes may either reinforce or oppose the general flow of air depending on the local circumstances. Finally, in some weather situations the trade winds are replaced by other general winds, some of which are not nearly as uniform in direction or speed.

Over the ocean around Hawaii, average wind speeds are highest during the summer trade-wind period. From May through September wind speeds over the ocean exceed 12 mph 50 percent of the time. These winds, 80 to 95 percent of the time, are from the northeast quadrant. The rest of the year, when trade winds are not quite as prevalent, wind speeds are in excess of 12 mph about 40 percent of the time. It is during this time that light, variable winds are most frequent and this more than balances the fact that winter is also the time of occasional very strong winds – winds stronger than those experienced during the summer except with the rare occurrence of a tropical system.

When the trade winds are moderate to strong, in excess of 14 mph, they dominate the flow of air across wide reaches of the lowlands. In contrast, light trade winds are commonly felt only along the eastern to northern coasts of the islands and in exposed locations in the hills. With such light trades, there are often well defined local breezes along sheltered leeward coasts; and in some

areas, as on the Kona Coast of Hawaii and in the Kihei area on Maui, these local sea and land breeze circulations occur not only when the overall wind is light but also when the trade winds are moderate to strong. In these locations, the local sea and land breezes may be reinforced by the trades.

On a few exposed headlands and in mountain passes so oriented as to catch and concentrate the full force of the trades, winds above 40 mph may occur several days each month. In nearly all other locations, however, such winds occur only occasionally, and then only as the result of a major storm, a cold front passage or an unusual local situation.

Major storms are chiefly events of the winter season. They may yield very high winds from any direction. In the lowlands, wind speeds associated with these storms have exceeded 60 mph over a period of one to two minutes, and 80 mph momentarily in gusts. At Mauna Loa Observatory, at an elevation of 11,150 feet, gusts to over 100 mph have been recorded. In any major, wind-producing storm that extreme wind speeds may vary significantly from one place to another, due to the peculiarities of the storm and to the effects of terrain. Significantly higher winds speeds are often found in restricted areas.

Occasional violent winds, often of limited extent, have been observed in a few areas. They reach speeds of 60 mph or greater and have blown down well-rooted trees as well as power lines designed to withstand very high wind loads. These winds occur infrequently in many sparsely settled areas on the slopes of the mountains of Hawaii and Maui, or near the mouths of canyons along the base of these mountains. They are, however, known best in the settled areas of Kula and Lahaina on Maui.

The Kula winds are strong downslope winds. They occur in the Kula District along a section of the lower slopes on the west side of Mt. Haleakala. The winds tend to be strongest between 2,000 and 4,000 feet above mean sea level. In this zone there may be episodes of downslope winds with speeds of over 40 mph as often as twice a year. However, winds with speeds in excess of 60 mph occur with less frequency.

The Lahaina winds are another downslope wind, but of somewhat different character from those of Kula. In the Lahaina area they have been given the name of "*lehua* winds" after the *lehua* tree whose red blossoms fill the air when these strong winds blow. They issue from the canyons at the base of the main mountain mass of western Maui, where the steeper canyon slopes meet the more gentle piedmont slope below. These winds have been reported from both the western and southern side of the western Maui mountains. They are infrequent. When they do occur, however, they are extremely violent, with wind speeds of 80 mph or greater. They have been known to demolish buildings, uproot trees and cause severe damage throughout whole fields of sugarcane. That they are downslope winds is evident from their being hot and dry. The mountains of western Maui are less than 6,000 feet high as contrasted with the 10,000-foot height of Haleakala, and these local Lahaina winds are caused, at least in part, by the funneling of strong trade winds through mountain gorges.

Aside from the more violent mountain winds, there are light to moderate mountain winds in many areas on the larger mountains of Hawaii and Maui and in a few local areas in the smaller

mountains of the other islands of the State. The usual regime is to have upslope winds by day and downslope winds by night, and this circulation takes its place with that of the sea-and-land breezes in coastal locations as a finer, yet important, feature of the State's overall wind regime.

Due to the diverse geography, the moisture distribution within the air that moves across Hawaii is far from uniform. Under trade-wind conditions, there is very often a pronounced moisture discontinuity at heights of between 4,000 and 8,000 feet. Below these heights the air is moist; above it is dry. The break occurs in association with a temperature inversion that is typically embedded in the moving trade-wind air, and represents a large-scale feature of the Pacific Anticyclone. From the surface up to the inversion, the temperature decreases with increasing height in a quite uniform manner. The moisture is well distributed throughout this lower layer, and the moisture content of the air is relatively high. At the base of the inversion the temperature increases by several degrees, sometimes quite suddenly. These higher temperatures may extend upward for several hundred feet before the temperature begins once more to decrease upward. The significance of the inversion climatically is that it tends not only to produce a lower, more moist layer as against a higher, more dry layer, but it also tends to suppress the vertical movement of air and hence to restrict cloud development to the zone beneath the base of the inversion.

The inversion is present 50 to 70 percent of the time. Its height fluctuates from day to day, but it is usually between 5,000 and 7,000 feet. On trade-wind days, when the inversion is well defined, the clouds develop most markedly below these heights with only an occasional cloud top breaking through the inversion. These towering clouds form chiefly along the mountains in particular local situations where the incoming trade-wind air converges as it moves up a valley and is forced up over the mountains to heights of several thousand feet. The overall result is a complicated cloud pattern, typically with scattered to broken clouds above the lowlands at a fairly uniform height on the windward coasts and with more dense cloud masses along the mountains; these clouds are generally of uniform height, but with some smaller masses that bulge upwards.

On days when there is no inversion the vertical development of clouds is much greater. There may then be towering clouds at sea as well as over the land. There is still a tendency for the maximum cloud development to occur along the mountains with individual clouds likely to tower upward 15,000 feet or more. With a storm or other disturbance in or near the islands, the cloud pattern may become very complicated, often with very high cirrus clouds in different arrangements, with layered or cellular cloud decks beneath them at heights of 8,000 or 15,000 feet, and with masses of cumulus clouds rising from near the surface to 30,000 to 50,000 feet. At the other extremes, there are occasional days without an inversion when the sky is almost cloudless, and a few times a year it is possible to scan the entire sky without seeing a single cloud.

Throughout the lowlands in windward areas in the islands the sky is cloudy about 40 to 60 percent of the time during the daylight hours and is clear 15 to 20 percent of the time. In downtown Honolulu, which is to the leeward of a low mountain range, these values are 27 percent cloudy and 25 percent clear during the daylight hours. In leeward locations well screened from the trade winds, as along the west coasts of Maui, Kauai and Oahu, the percentage

of clear daylight conditions ranges from 30 to 60 percent and cloudy conditions decrease to less than 20 percent. However, in these leeward areas as in those to the windward, the cloudiness increases rapidly as the mountains are approached.

In general, windward areas tend to be cloudier during the summer, when trade winds and trade wind clouds are more prevalent, while leeward areas – which are less affected by trade-wind cloudiness – tend to be cloudier during the winter, when general storms and frontal passages are more frequent. The cloudiest zones of all are at and just below the summits of the mountains of Kauai, Oahu, Molokai, Lanai and western Maui, and at elevations of 2,000 to 4,000 feet on the windward sides of Haleakala, Mauna Loa and Mauna Kea. In these locations, the sky is cloudy more than 70 percent of the time.

In contrast, the areas of least cloudiness include the high mountains above about 8,000 feet. Here the skies are normally clear between late evening and forenoon, but tend to become cloudier during the middle part of the day. The description by Price and Pales of the usual regime at the Mauna Loa Observatory is representative of most high mountains:

“...a typical day at the Observatory may dawn bright and clear. Visibility is excellent. Peaks on other islands 80 miles distant and more are distinguishable without difficulty. The trade inversion lies several thousand feet below, and trapped beneath it are the clouds and the bulk of the water vapor, dust, and haze. In the clear atmosphere, insolation is intense.... By early afternoon, moister air appears to be seeping upward along the mountain. The humidity increases and fractocumuli (broken cumulus clouds) advance up the slopes. In the next hours the observatory may be briefly enveloped in fog or light rain; but by evening the clouds have dissipated and the conditions which opened the day return. Nights are generally clear.”

The usual clarity of the air in the high mountains is associated with the low moisture content of the air. Except for occasional periods of a few hours duration, which accompanies the arrival of more moist air from below, the relative humidity is generally below 40 percent, and it often falls to 10 or less. Such low humidities are characteristic of the zone above the inversion.

Below the inversion, the lowlands and along the lower mountains, the relative humidity commonly averages 70 to 80 percent in windward areas and 60 to 70 percent in leeward ones. Winter relative humidities are somewhat higher than summer ones; and in terms of daily variations the maximum values occur with the minimum temperatures, during the late night and very early morning. Nighttime values in the cooler and rainier areas often exceed 90 percent, but are more frequently between 70 to 80 percent in the leeward lowlands and other drier localities. Afternoon values are commonly between 60 to 70 percent in the windward and uplands regions, not infrequently between 50 to 55 percent in the drier, warmer coastal zones, and seldom fall below 40 percent anywhere at elevations below the trade wind inversion. Thus, except on the high mountains, the general regime in Hawaii is one of high humidities.

Precipitation– If the islands of the State did not exist, the average annual rainfall upon the water where the islands actually lie would be about 25 inches. Instead, the actual average is about 70 inches. (This is equivalent to not quite 8 trillion gallons of water per year.) Thus, the islands extract from the air that passes across them about 45 inches of rainfall that otherwise would not fall. That the mountains are dominantly responsible for this added water is evident from annual

rainfall maps, which show the tremendous amounts of rainfall deposited in mountainous areas in the average year. In many mountainous areas of the State these depths exceed 240 inches, or 20 feet. At Mt. Waialeale, on Kauai, the annual average reaches the extraordinary total of about 450 inches. This is possibly the highest recorded annual average in the world.

It may seem strange that there can be problems of water supply in parts of Hawaii. However, not only is there very substantial a water loss due to evaporation, transpiration, runoff and percolation into the porous lavas, but the rainfall distribution is exceedingly uneven. There are very few areas elsewhere in the world where rainfall gradients are as steep as they are in Hawaii. In many places in Hawaii, the annual rainfall gradient exceeds 25 inches per mile; that is the rainfall increases (or decreases) 25 inches for each mile transversed along a straight line. In a very extreme instance, the gradient is over 100 inches per mile along the 2.5 mile line from Hanalei Tunnel to Mt. Waialeale on Kauai. These steep rainfall gradients and the presence of very dry areas as well as very wet ones result in there being abundant water overall, but with great surpluses in some areas and great deficiencies in others. The major problem of water supply is therefore one of distribution rather than one of a general water shortage.

The zones of highest rainfall on the flanks of the large, high mountains of Haleakala, Mauna Loa and Mauna Kea lie at elevations of 2,000 to 4,000 feet. In contrast, on the remainder of the mountains, the highest rainfall is along or near the crest line. The difference lies in the fact that the incoming ocean air that is the source of rain usually flows across the lower mountains, whereas it largely flows around the higher mountains. The trade-wind inversion, which tends to suppress vertical lifting of the air, is usually above the level of the crests of the low mountains and is never above the level of the crests of the high mountains.

The driest areas are on the upper slopes of the high mountains, on leeward coasts or in leeward locations in the interior of the islands as in central Maui. In the driest of these areas the average annual rainfall is less than seven inches around Kawaihae Bay near the northern end of the west coast of Hawaii.

In many areas of intermediate rainfall the natural landscape indicates great aridity. Xerophytic (drought-resistant) plants, widely scattered across otherwise barren ground, are sometimes found in areas in which the annual rainfall is 100 inches or more. This seeming anomaly is the result of very high infiltration rates in the volcanic rocks and soils so that the water that falls as rain moves rapidly downward to great depths in the regolith and is available to the plant only to a sharply limited extent. Areas of this kind are most commonly found on the relatively young island of Hawaii.

Except for the Kona coast of Hawaii, at elevations below 2,000 feet throughout the State, winter is the season of highest average rainfall. The contrast in rainfall is most pronounced between low elevations in the areas with low annual rainfall. The contrast is least in areas of higher annual rainfall, as at Hilo. Further, within the extremely rainy areas above 2,000 feet the winter rainfall maximum disappears in many localities and instead there is fairly uniform, superabundant rainfall all months of the year. Thus at Kukui, Maui, at an elevation of 5,788 feet, the average monthly rainfall is 32.81 inches in winter and 33.49 in summer, with April the wettest month (40.78) and October the driest (23.33). The average annual rainfall at Kukui is slightly over 399 inches. Finally, in the very high mountains where conditions are dry, winter is

again the rainier of the two seasons. This is indicated by the observations at Mauna Loa Observatory, with an annual precipitation of about 19 inches, winter precipitation averages 2.10 inches per month and summer precipitation averages 1.10 inches.

The Kona coast of Hawaii has a unique seasonal rainfall regime. The summers are wetter than the winters. At Napoopoo, for example, February is the driest month and September is the wettest. Napoopoo, elevation 400 feet, has an average annual rainfall of 34.08 inches. The summer maximum on the Kona coast is associated with the fact that in the well-protected Kona area, which lies to the leeward of Mauna Loa and Mauna Kea, has a distinctive local circulation. The winter storms that contribute the bulk of the average annual rainfall in other lowland regions of the State contribute less rain to the Kona coast.

In the lowlands at all times of the year, rainfall is most likely to occur during the nighttime or in the morning hours and least likely to occur during mid-afternoon. Correspondingly, not only is rainfall more frequent at night, but also the total nighttime fall averages more than the total daytime fall when two 12-hour periods are compared. A study of the rainfall in Honolulu showed that 59 percent of the annual rainfall total fell, on average, between 8:00 p.m. and 8:00 a.m. In general, this diurnal variation was far more pronounced in summer than in winter, especially with respect to rainfall frequency. Thus in summer, rainfall during the early morning hours (3:00 to 8:00 a.m.) is about twice as frequent as during the late morning and early or mid-afternoon (11:00 a.m. to 4:00 p.m.)

The more pronounced diurnal variations in summer is associated with the fact that most summer rainfall consists of trade-wind showers and these showers are most likely to occur at night. In winter most of the rainfall in the lowlands occurs in general storm situations, and these are as likely to take place during the daytime as at night.

At elevations of a few thousand feet, where trade-wind showers contribute very substantially to the total rainfall in winter as well as summer, the nighttime rainfall maximum is better marked in winter than it is in the lowlands. However, on the very high mountains above the trade-wind inversions, the diurnal cycle is reversed, and the late afternoons are the time when light rains are most apt to occur as accompaniment to the arrival of moist air carried upward by the upslope wind from below.

In most parts of the tropics rainfall is highly variable from one year to another and Hawaii is no exception. Even in areas where the rainfall is very high and the monthly averages are above 10 inches, the rainfall of particular months may vary by 200 to 300 percent from one year to another and there may be occasional months with only one or two inches of rain.

The great variability in annual rainfall is evident from the extreme values at several different stations during their periods of record. In downtown Hilo, in 79 years, the highest annual total was 207 inches; the lowest 72. At Honolulu, in 62 years, the extreme values were 46 inches and 10 inches; at Mana, Kauai, in 61 years, 48 and five inches. During a period of 23 years at Kukui, Maui, the extremes were 578 and 250 inches.

Rainfall variability is far greater during the winter, when occasional storms contribute appreciably to rainfall totals, than during summer, when trade-wind showers provide most of the rain. In January, Hilo has received less than 0.2 inches of rain, but also more than 50 inches. Honolulu has received as little as 0.12 of an inch and as much as 18 inches. The highest January total in 23 years at Kukui was 58 inches. The extreme August rainfall totals at Hilo the range from two to 38 inches. At Honolulu, it was from a Trace (nothing measurable) to four inches. And, at Kukui it was from 10 to 88 inches.

With such wide swings in rainfall it is inevitable that there are occasional droughts, sometimes with severe economic losses. The real drought years are the ones where the winter rains fail. A deficit of winter storms can affect any portion of the State. Significant rainfall deficits hit hardest in the normally dry areas which depend chiefly on winter rains and receive little rain from the trade wind showers. In these localities the small amount of rainfall that occurs during the usual dry summer season is insufficient to prevent severe drought. Severe droughts are usually limited to an area of 50 square miles or so, but they may be very costly because of the increased water costs. Where irrigation is not practiced, they may destroy or severely damage the crops and range grasses.

Torrential rainfall is common in all parts of Hawaii except the very high mountains, although it has been known to occur even there. Yet it is also true that in Hawaii very light showers are extremely frequent in most localities. On windward coasts, for example, there may be as many as 10 brief showers in a single day, not one of which is heavy enough to produce measurable precipitation. Trade-wind weather yields many light showers in the lowlands, whereas the torrential rains are associated with other weather regimes, e.g. a sudden surge in the trade-winds or with a major storm.

Extreme rainfall intensities are high in Hawaii. To take the most extreme instance of record, during the storm of January 24-25, 1956, over 38 inches of rain fell at the Plantation Office, Kilauea Sugar Plantation, Kauai, within a 24-hour period, out of a storm total of 43.5 inches. During the same storm six inches of rain fell during a single 30-minute period and about 12 inches fell in one hour. The 38-inch value for 24-hours is conservatively low, because the gage was already overflowing when it was emptied for the first time. The six-inch value is correct within one or two tenths of an inch; the 12-inch value for one hour is an estimate only – again because of overflow – and may be in error by as much as an inch.

Rainfall intensities and totals as high as the extraordinary values just cited appear to have occurred when a current of moist, unstable air, converges as it moves up a narrowing valley, and at the same time is forced to rise abruptly over steep mountains. Such special topographic circumstances are not essential to the occurrences of torrential rains. For example, in 24 hours, Hana, Maui has had 28 inches of rain; Opaepa, Oahu, 26 inches; and Hilo, Hawaii, 19 inches, though none of these are favorably situated with references to topographic surroundings conducive to the occurrence of very high rainfall intensities. The most copious rains in Hawaii frequently do not occur in localities having the greatest average rainfall; nor is it uncommon during such storms for relatively dry areas to receive within a single day, or even a few hours, totals approaching their mean annual rainfall.

At Honolulu the greatest 24-hour rainfall was that of March 5-6, 1958, when 17.41 inches was recorded at the Federal Building in the downtown area. The gage where this total was recorded was situated well away from local topographic influences that might cause excessive rainfall. In general, all stations in Hawaii which have at least 50 years of record have experienced daily rainfalls of at least eight inches, and the majority have experienced falls of 12 inches or more. Torrential rains, falling on Hawaii's steep slopes and small drainage basins, often generate flash floods that erode fields, cause landslides and damage homes, business and infrastructure.

For many purposes it is convenient to think of Hawaiian weather in a very much simplified way, in terms of trade winds and non-trade-wind conditions. Most of the time the weather is dominated by the trade winds. There are light to moderate trade-wind showers on windward coasts. In the rainier mountain areas these showers are often moderate to heavy and may merge to produce continuous rain for hours or days. In the leeward areas occasional light trade-wind showers may drift over from the mountains to windward, except that in such completely sheltered lees as the Kona Coast of Hawaii, sea breezes ascending the mountain slopes may produce light to occasionally heavy showers in the late afternoon and early evening. On the upper slopes of the highest mountains conditions are dominantly clear except for occasional intrusions of moist air from below, when light rains may fall, especially in the afternoon.

Non-trade-wind conditions are quite different. When the winds are light and variable, moist air may move slowly onto the islands, typically from a southeast through southwest direction. Then there may be intense local storms. At other times there may be major storms, as when a cold front crosses the islands or when a large storm system passes. Major storms may produce heavy rains in many localities. They can produce snow and ice in the high mountains, and sometimes even hail. Storms usually occur during a breakdown in the trades (although some of Hawaii's heaviest rains have occurred when trade winds were overlain by low pressure areas higher in the atmosphere); and though they are relatively infrequent, they are an important and integral part of the total weather scene.

Intense local rainstorms other than those that occur under trade-wind conditions are small features that seldom cover more than a few square miles and some times less than a single square mile. They occur most typically in the late afternoon or early evening. In some areas in which there are well-developed sea breezes, such as Kona, Hawaii, they are common occurrences, especially in summer. In most areas, however, they are apt to occur on only a few days per year when the overall winds are light and variable or when there is a gentle flow of air from a southerly direction. Storms of this character may occur at any time of the year.

Intense local storms are sometimes accompanied by lightning and thunder. These thunderstorms also occasionally accompany very intense rainfall along a cold front moving across the islands. In the lowlands, thunderstorms occur an average of only five to 10 times a year. Thunderstorms are reported somewhere in the State about 20 to 30 days a year, and more often in winter than in summer.

Waterspouts and other funnel clouds are not uncommon in the Hawaiian area, about 20 of them being sighted in the average year. Often they are accompanied by towering cumulus clouds and rain, although they have also been observed under trade wind conditions. Occasionally a

waterspout will drift onshore and do some minor damage, and small tornadoes have been known to form over the islands with the same effect.

Hail falls somewhere in Hawaii between five and 10 times in the average year. Almost always it is quite small, ¼ inch or less in diameter, but on several occasions hail the size of marbles, and discs about five-eighths of an inch in diameter, have been reported. Trees and leafy crops have been battered by hail from time to time, but this is an infrequent occurrence and the areas affected are small. Many lifelong residents of Hawaii have never experienced hail.

There are four classes of disturbances that produce major storms. Sometimes a cold front sweeps across the islands bringing with it locally heavy showers and gusty winds. Sometimes a low pressure system moves past bringing widespread heavy rains, often accompanied by strong winds. These Lows are known as Kona storms, a term originally reserved for the slowly moving subtropical cyclones that occasionally enter the Hawaiian area. They include situations in which the low-pressure area is not well marked, but instead consists of a low-pressure trough into which air feeds from either side. The third class of disturbance is the true tropical storm or hurricane. These are rare, but may pass close enough to the islands to yield heavy rains, high winds and great waves. Also meriting treatment as a separate and fourth class of disturbance are those instances of severe weather attributable to low pressure systems (Lows and troughs) in the upper atmosphere. Of particular interest are those which occur in the presence of trade winds in the lower atmosphere.

During some winter seasons as many as six to eight well-defined cold fronts may sweep across two or more islands. Because of its location at the northwest end of Hawaii, the Island of Kauai has a few more cold front storms each year than do Oahu and the other islands. Sometimes the southernmost edge of a mass of cool air will barely encroach upon Kauai and will move eastward without reaching as far as Oahu. At other times, cold fronts that pass Oahu may dissipate before reaching the southern islands.

When a cold front passes there may be heavy rains. Typically these rains are spotty, with several inches falling in some areas and much less in others. Winds are gusty, with wind directions mainly from the north and northwest. The cool air that follows the passage of the front brings relatively cloudless skies. In the lowlands, nighttime temperatures may drop to between 59 and 64° F. Afternoon temperatures are commonly in the mid 70s.

The winds accompanying a cold front are usually brisk, but they may be more than merely brisk in some localities. Every few years, on average, a cold front will produce winds that blow down trees or rip the roofs from buildings within a limited area. From time to time cold front passages have given rise in the vicinity of the islands to waterspouts or to small tornadoes. Meanwhile, the high mountains of Haleakala, Mauna Kea and Mauna Loa receive snow on their upper slopes.

Kona storms, like cold front storms, are features of the winter season. They are so-called because they often bring winds from *kona* or leeward directions. The rainfall in a well-developed Kona storm is more widespread and more prolonged than in the usual cold-front storm. Kona storm rains are usually most intense in an arc, or band, extending from south to east of the storm and well in advance of its center. An entire winter may pass without a single well-

developed Kona storm. More often, however, there are one or two such storms a year. Some winters there are more, four or five.

Kona rains last from several hours to several days. The rains may continue steadily, but the longer lasting ones are characteristically interrupted by intervals of lighter rain or even partial clearing, as well as by intense showers interspersed in the more moderate regime of continuous, steady rain.

Hurricanes are rare in Hawaii. Tropical storms, with sustained winds of less than 74 mph, are more frequent. A tropical storm will pass sufficiently close to Hawaii every year or two, on average, to affect the weather in some part of the Islands. Unlike cold front and Kona storms, hurricanes and tropical storms are not limited to winter. They are, however, more likely to occur from July through December.

Hurricane Iniki was the most powerful hurricane to strike the State of Hawaii, and one of the most costly hurricanes in the United States. Its eye passed directly over the island of Kauai on September 11, 1992, causing six deaths, 100 injuries and more than \$3 billion (1992 figure) in damage. When the storm made landfall on the southern coast of the island, maximum winds were 140 mph with higher gusts, making Iniki a Category 4 hurricane on the Saffir-Simpson scale. The damage on Kauai was extensive. More than 14,000 homes were either damaged or destroyed, with many losing their roofs or flattened entirely. Hotels and condominiums facing the ocean were also damaged. The economy also took a hit as sugar cane, bananas and papaya were either heavily damaged or destroyed, and tourists chose another island the visit.

At other times, severe weather in the Hawaii is attributable to low pressure areas which are well developed in the upper atmosphere (rather than near sea level). The weather which accompanies these upper Lows or trough, towering cumulus clouds, thunderstorms, intense and widespread rain, often resembles that of a Kona storm and may be mistaken for one, except for the absence of the persistence, and sometimes strong, southerly winds that frequently accompany Kona storms. The surface winds during these events may be from almost any direction.

Between October and May, major storms may deposit a foot or more of snow on the upper slopes of one or more of Hawaii's highest mountains: Haleakala, Mauna Kea and Mauna Loa. After an especially heavy fall, patches of snow may extend to as low as 7,000 feet, but snow below about 11,000 feet quickly vanishes, since even winter air temperatures in Hawaii are ordinarily above freezing to altitudes of 13,000 feet and higher. Hence there is no snow cover for more than a few days on these summits.

Climate and the Economy- In terms of dollars, government activities (local state and federal), agriculture, industry, commerce and especially tourism play important parts in Hawaii's economy. The mid-Pacific location of Hawaii has made it important militarily.

Sugar cane is a two-year crop in Hawaii and most of it is raised under irrigation. The abundance of water in the State and the warmth form the climatic basis for this crop. Pineapple is another important crop. It occupies lands that are generally dry since the crop requires little water and

since low cloudiness and high sunshine are essential during the ripening period. The crop requires 18 to 20 months between planting and harvesting.

Sugar and pineapple lands are in the lowlands, generally below 2,000 feet. In contrast, the rangelands that support the livestock industry chiefly occupy the higher elevations, mostly on Hawaii and Maui. Except where small herds are maintained for dairying, these are the drier lands. Other agricultural activities of the State include the raising of tropical fruits, nuts, coffee and vegetables. Coffee is raised on the Kona coast, where the wet summer and the dry period of early winter are especially favorable to its production.

The climate is a principal basis for the tourist industry of the State. The mild temperatures are an asset as are the low rainfall and generally sunny conditions in such leeward locations as Waikiki and Kona. The trade-wind breeze is also an important element because on the warmer days it often lowers the sensible temperatures appreciably, making conditions for more pleasant than the temperature and humidity values alone would indicate.

In general, the climatic conditions in Hawaii, especially in the lowlands, favor many kinds of agricultural, commercial and industrial enterprises. The summers are warm, but not hot. The winters are warm. There is water for domestic, industrial and agricultural uses in all but the very driest parts of the State.